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TITLE: SIMULATIONS OF THE EFFECTS OF MOBILE IONS ON THE RELATIVISTIC BEAM-PLASMA INSTABILITY FOR INTENSE BEAMS

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SIMULATIONS OF THE EFFECTS OF MOBILE IONS ON THE RELATIVISTIC BEAM-PLASMA INSTABILITY FOR INTENSE BEAMS

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Abstract

Particle-in-cell simulations of the beam-plasma instability for intense relativistic electron beams in dense plasmas show rapid heating of the electrons to multi-kilovolt temperatures. The resulting hydrodynamic motion of the plasma results in density gradients that degrade the interaction. Heat flow out of the plasma is found in some instances to limit the gradient formation process.

Introduction

The concept of using intense relativistic electron beams to heat high-density plasmas for inertial fusion is currently being investigated at Los Alamos [1-3]. The heated plasma surrounding the fusion pellet provides an efficient transfer of energy from the beam to the pellet and avoids the preheat problem associated with high-voltage beams. In order for this concept to be a viable inertial fusion driver, the beam must couple efficiently to the plasma.

Previous studies have shown that efficient energy coupling is possible via the relativistic beam-plasma or two-stream instability [4]. This instability operates at the plasma frequency and most of the energy transfer is to the plasma electrons. Furthermore, it is found that plasma density gradients may degrade the interaction. The heating of the plasma electrons raises the sound speed and allows the ions to move, thus forming density gradients.

This paper reports the results of a numerical study of the self-consistent gradient formation process, performed with the particle-in-cell simulation code CCUBE [5]. The code is 2½-dimensional, fully electromagnetic, and relativistic. The simulations were performed in the r-z plane of cylindrical coordinates.

Simulation Parameters

An exhaustive parameter study of this problem is impossible. Therefore, the parameters were chosen to approximate the parameters of recent experiments [2-3]. The simulations begin with an annular region of plasma enclosed by a conducting cylinder whose inside radius is 195 c/ω_p and whose thickness is 12 c/ω_p, where c is the speed of light and ω_p is the plasma frequency. Into this region is injected an annular electron beam with Lorentz factor $\gamma = 2$ (500 keV) and current 23 kA. The beam is monoenergetic, but it has a mean angular scatter about the axial direction of $\bar{\theta} = 0.03$. The inside radius of the beam is taken to be 200 c/ω_p and the thickness is 2 c/ω_p. The simulations are performed with dimensionless parameters; but for a plasma density of 10^{16} cm^{-3}, these dimensions correspond to a beam with an inner radius of 1 cm and a thickness of 100 μm. All simulations were performed with an axial magnetic field, $\omega_c/\omega_p = 0.3$, where ω_c is the electron cyclotron frequency.

The beam particles are absorbed when they strike the conducting boundaries and the plasma particles are thermally re-emitted from the walls with a temperature of a few eV. The injection velocity of the beam particles is held constant and the charge of the particles is increased over a period of about 150 ω_p^{-1} to gradually establish the beam current and allow self-consistent return current and charge neutralization by the plasma. It is adequate to simulate only the annular region about the beam because the instability is essentially electrostatic and the fields vanish a couple of c/ω_p outside the beam [6]. Also the self-consistent return current flows within a couple of c/ω_p of the beam. The simulation cell size is 0.4 c/ω_p × 0.4 c/ω_p, 9 beam particles/cell, and 4 electron and 4 ion particles/cell are used.

The Effect of Gradients

For a uniform plasma, the beam-plasma instability is an absolute instability growing in both space and time [7, 8]. Figure 1 shows a series of snapshots of the phase space of the beam as the instability develops for immobile ions. The beam is injected at z = 0 and the instability grows spatially until particle trapping leads to nonlinear saturation. Trapping occurs when the phase space becomes double valued. Because the instability is absolute, the trapping point gets shorter in time. For a 10^{16} cm^{-3} density plasma, the simulation length

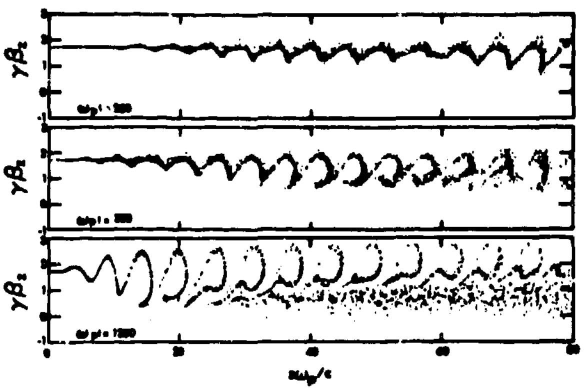

Fig. 1. Beam phase space plots for uniform plasma and immobile ions showing absolute instability.

(80 c/ω_p) corresponds to 4 mm. The trapping length can be seen from Fig. 1 to become less than 1 mm.

If the gradients are weak enough, the instability will behave qualitatively like the uniform density case. However, if the gradients are stronger, the instability becomes convective, which limits the trapping length [9]. Figures 2 and 3 show phase space snapshots from two simulations with immobile ions but with linear plasma density gradients. In Fig. 2, the plasma density varies from 0.8 at $z = 0$ to 1.0 at $z = 80\ c/\omega_p$ in the dimensionless units of the code. As can be seen, the instability retains its absolute character and the trapping length shortens in time. For Fig. 3, the density variation is from 0.7 to 1.0. In this case the instability becomes convective and the trapping length ceases to shorten.

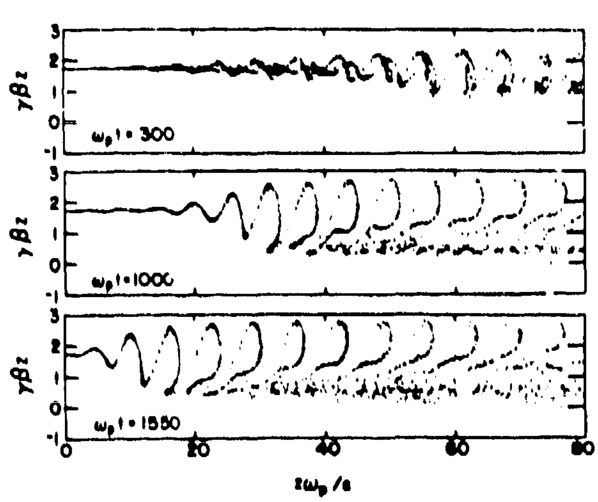

Fig. 2. Beam phase-space plots for plasma with 20% density variation across the simulation region showing uniform-like absolute instability.

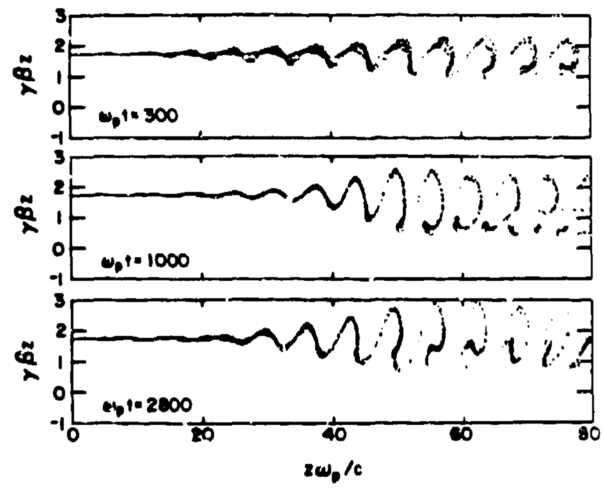

Fig. 3. Beam phase-space plots for plasma with 30% density variation across the simulation region showing the instability becoming convective.

Mobile Ion Simulations

Figure 4 shows phase-space snapshots for an initially uniform system with mobile ions of the proton mass. Note that the system is only 40 c/ω_p long. The trapping length shortens and then begins to lengthen until finally the trapping length exceeds the length of the plasma and the beam stops depositing energy. The energy phase space for the plasma electrons at $\omega_p t = 600$ is shown in Fig. 5. It shows the electrons being preferentially heated near the center of the plasma to near 1 keV. The energy loss

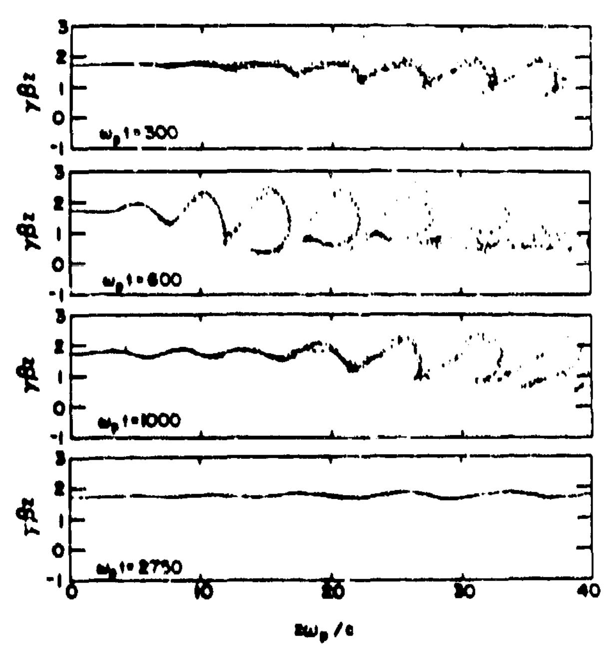

Fig. 4 Beam phase-space plots for mobile ions showing quenching of the instability resulting from ion motion.

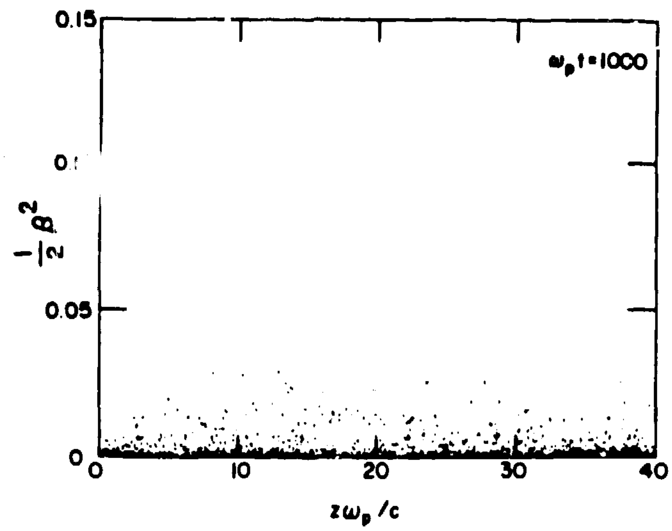

Fig. 5. Energy-phase space plot for plasma electrons showing localized heating.

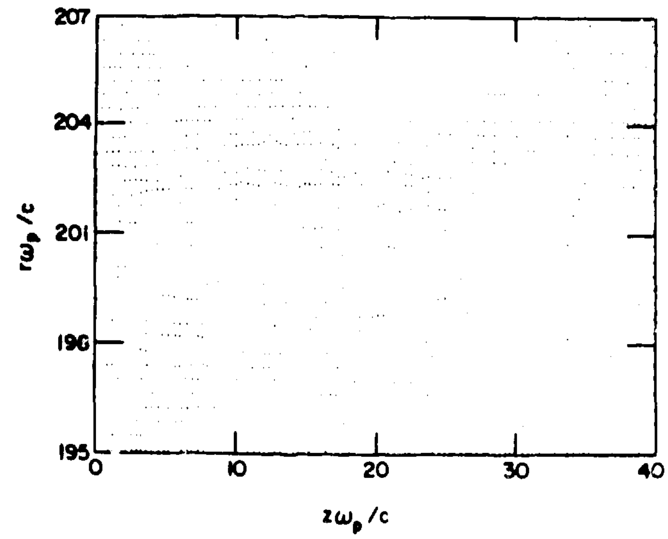

Fig. 6. Ion particle plot showing movement from initially uniform distribution.

appears localized in space near the point of trapping. This raises the ion acoustic speed enough to allow the ions to move freely across the magnetic field dragging the electrons with them. This results in a localized density depression forming an axial plasma density gradient. The ion positions are shown at $\omega_p t = 1000$ in Fig. 6. For these parameters the gradient relaxes very slowly so the interaction remains quenched, at least up to $\omega_p t = 2750$.

However, for a longer system as shown in Fig. 7, the trapping length may remain shorter than the plasma region. The thermal re-emission of the plasma electrons from the boundaries provides a means of energy loss so the plasma temperature ceases to increase, and the beam continues to lose energy. Eventually the plasma ions become heated, which also tends to smooth the gradients. The ion positions are shown in Figs. 8 and 9. Near $\omega_p t = 1000$ the localized motion of the ions produces an axial density gradient. Because the system is longer than in the case discussed previously, the interaction length can increase without stabilizing. Later, the interaction reaches a dynamic equilibrium where localized heating produces a gradient that weakens the interaction followed by a relaxation of the gradient, which strengthens the interaction, and the cycle repeats.

The fraction of the beam energy lost is a complicated function of time and the plasma uniformity [10]. These simulations showed as much as 50% loss for the uniform case compared with 15% for the last case discussed. If the ion acoustic speed divided by the ion cyclotron frequency can be kept smaller than the beam thickness, the magnetic field will prevent

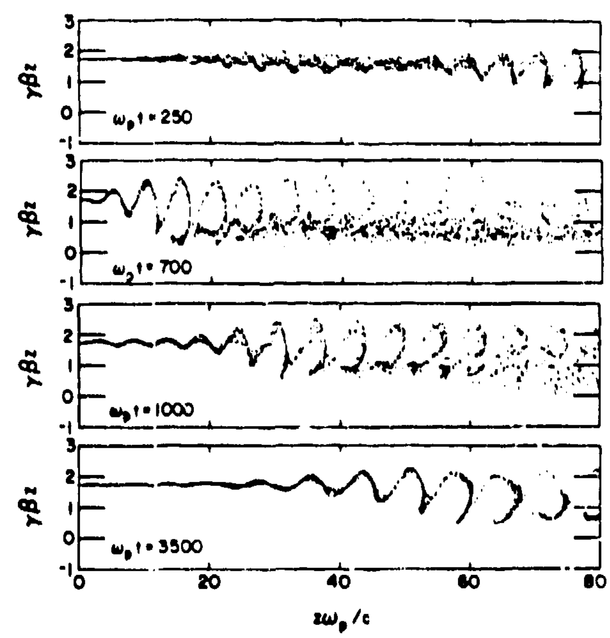

Fig. 7. Phase-space plot for mobile ions in longer system showing the effect of gradient formation making the instability convective but remaining unstable.

gradient formation from radial diffusion of the plasma. This can be achieved by heating higher density plasmas. Furthermore, significant cooling of the plasma electrons can occur due to radiation, an effect not included in these simulations.

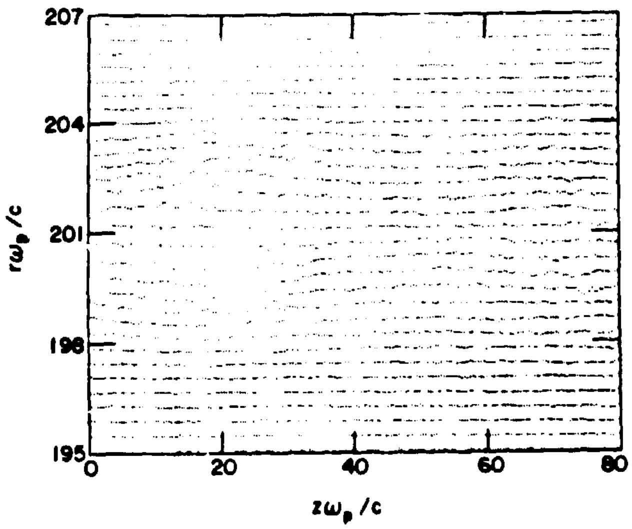

Fig. 8. Ion positions for the case in Fig. 7 at $\omega_p t$ = 1000.

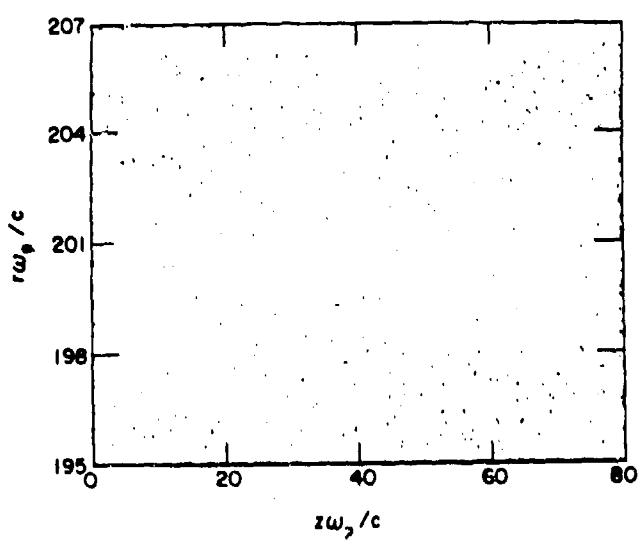

Fig. 9. Ion positions at $\omega_p t$ = 3500.

Acknowledgments

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References

1. L. E. Thode, Los Alamos Scientific Laboratory report LA-7715-MS (1980).
2. M. D. Montgomery, J. V. Parker, K. B. Riepe, and R. L. Sheffield, Appl. Phys. Lett. 34, 217 (1981).
3. H. A. Davis, C. A. Ekdahl, and O. Willi, paper 6P17, this conference.
4. L. E. Thode, Phys. Fluids 19, 831 (1976), and references therein.
5. M. M. Campbell, D. J. Sullivan, and B. B. Godfrey, Mission Research Corporation report AMRC-R-341 (1982).
6. M. E. Jones, Phys. Fluids 26, 1928 (1983).
7. K. Evans and E. A. Jackson, Phys. Fluids 13, 1885 (1970); R. J. Briggs, Advances in Plasma Physics, edited by A. Simon and W. B. Thompson (John Wiley Interscience, New York, 1971).
8. M. E. Jones, D. S. Lemons, and M. A. Mostrom, to appear in Phys. Fluids (Oct. 1983).
9. M. L. Vianna and A. Bers, Notas De Fisica 6, 147 (1974); and M. E. Jones and M. A. Mostrom, Bull. Am. Phys. Soc. 27, 982 (1982).
10. D. S. Lemons, M. E. Jones, and H. Lee, paper 6P19 this conference.